1. NEHRP Final Technical Report Grant number G18AP00067:

Determining the Distribution of Slip Across the Northern San Andreas Fault System: through Long-Term Fault Slip Rates

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NEHRP Abstract:

Funding provided by the National Earthquake Hazards Reduction Program supported geomorphic field mapping and geochronologic investigations of offset alluvial fans, channels, terraces, and surficial material along the Rodgers Creek Fault to determine geologic fault slip rates over multiple late Quaternary timescales. The Rodgers Creek Fault is a major fault in the San Francisco Bay Area, California and is one of the most active faults within the northern San Andreas Fault System (e.g., UCERF3, 2015). Despite this, the fault's slip rate is poorly constrained. Through field mapping, we have identified three primary sites to determine late Quaternary slip rates. Geochronologic samples were collected in the field at each of the slip rate sites in order to date alluvial fans and terraces that are offset by the Rodgers Creek Fault. All 26 samples have been processed through necessary geochemical lab procedures. With our current results, we calculate an initial Holocene slip rate of 5.4 $^{+4.7}/_{-1.7}$ mm/yr (~4-10 mm/yr) since 4.6 $^{+3.3}/_{-2.6}$ ka for the northern Rodgers Creek Fault at Shiloh Ranch Regional Park, consistent with geologic slip rates determined on the fault located ~ 34 km to the south.

2. NEHRP Report

Introduction: Our study is located along an ~10 km section of the northern Rodgers Creek Fault from the UTM northing of 4263000 to 4270000 (Zone 10), adjacent to the town of Windsor, CA, in the Northern San Francisco Bay Area (Fig. 1). This section of the fault is of key importance because Quaternary geologic slip rates have not been determined for the Rodgers Creek Fault to the north of Santa Rosa. In this region, we have identified three slip rate sites through Quaternary geomorphic mapping, one in Shiloh Ranch Regional Park (Figs.1 and 2), one in Foothill Regional Park (Figs. 1 and 4), and one in Chalk Hill Winery, adjacent to North Brooks Rd (Figs. 1 and 5). At these three sites, in-situ cosmogenic ^{10}Be dating was applied to constrain the age of offset alluvial fans and fluvial terraces. A total of 26 samples were collected, all of which have been processed through necessary geochemical lab procedures. In the following sections preliminary geochronologic results, are discussed in conjunction with the respective slip rate sites. Here we summarize initial results from the first year of funding to study the Rodgers Creek Fault. A second year of funding is currently underway to refine interpretations presented here and to constrain the uncertainty on our slip rate estimates.

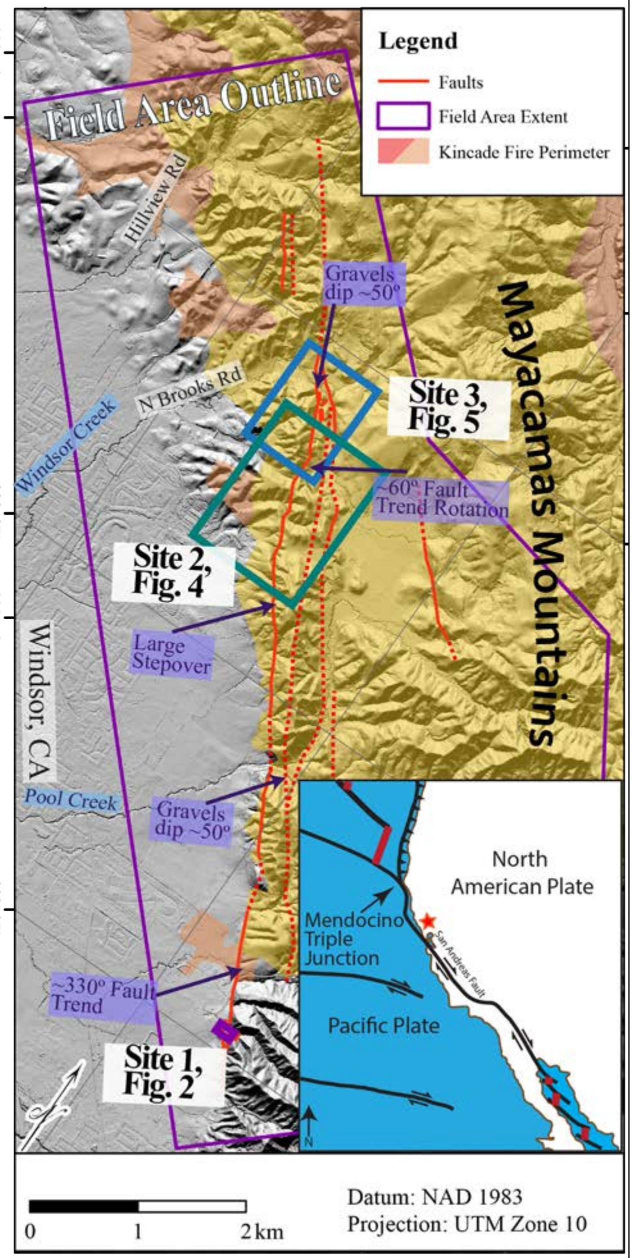

Fig.1. Location of field area delineating the Rodgers Creek Fault near Windsor, CA. The red star in the index map shows this location relative to the San Andreas Fault.

Geologic Setting: The San Andreas Fault System is a complex network of dextral strike-slip faults. In the northern San Francisco Bay Area, the fault system trends N30W (Wagner & Gutierrez, 2017), is 80-90 km wide and consists of multiple sub-parallel faults (McLaughlin and Nilsen, 1982). Here, geodetic block models estimate the main strand of the San Andreas Fault accommodates up to ~22 mm/yr of interseismic strain of the ~50 mm/yr of motion across the Pacific-North America (PA-NA) plate boundary (e.g., d'Alessio, et al., 2005; Evans et al., 2012). Known Quaternary geologic slip rates for faults east of the San Andreas Fault are: Hayward Fault [7.3-8.7

mm/yr] (Lienkaemper & Borchardt, 1996), Rodgers Creek Fault [6.4-10.4 mm/yr] (Budding et al., 1991; Schwartz et al., 1992), and Maacama Fault [6. 4-8.6 mm/y] (Prentice et al., 2014). Near the latitude of Santa Rosa, CA, the remaining ~28 mm/y of non-San Andreas slip is partitioned along faults such as the northern and southern Rodgers Creek, Maacama, West Napa, Bennett Valley, Bartlett Springs, Green Valley faults, and the East California Shear Zone, many of which have unknown Quaternary slip rates. This data gap leads to significant uncertainty in the nature of strain accommodated across the plate boundary and leaves seismic hazards in the region poorly constrained.

Today, the Rodgers Creek Fault represents a major structure within the PA-NA plate boundary and poses significant seismic hazards to Bay Area residents. The fault extends, at minimum, from the town of Healdsburg to San Pablo Bay (Hecker and Randolph Loar, 2018), where it then connects with the Hayward Fault (Watt et al., 2016), leading to a combined fault trace length of ~190 km. Together, the Hayward and Rodgers Creek faults, have the highest probability of Bay Area faults to rupture in the next 30 years (UCERF3, Fields et al., 2015). Near the town of Windsor, field mapping and high-resolution LiDAR image interpretation support findings that active horizontal deformation on the Rodgers Creek Fault is relatively localized to a narrow zone (Hecker and Randolph Loar, 2018) along the western edge of the Mayacamas Mountains and that the fault is active in the Holocene (Fig. 1).

Results: Initial fault mapping demonstrates that the northern Rodgers Creek Fault is composed of a series of subparallel and overlapping fault strands (Fig. 1). In the field, fault locations can be identified from well-preserved offset geomorphic landforms, including deflected and beheaded streams, linear ridges and valleys, and breaks in slope. Fault strands of the Rodgers Creek Fault are fairly linear and have a trend of ~330º (Fig. 1). Several small bend and stepovers are also present (Fig. 5a). Sub-parallel fault strands mapped 400m to 800m apart on the east and west sides of Foothill Regional Park (Fig. 4), bound a 5 km wide linear ridge at the western edge of the Mayacamas Mountains (Fig. 1). Sub-parallel faults appear to act as a large Quaternary stepover, which would lead to the transfer of fault slip across the ridge, creating this topography. Western fault strands show more pronounced tectonic geomorphology and appear to be the primary Holocene strand (Fig. 1). Field mapping indicates that the study area is principally composed of a network of overlapping alluvial fan deposits that have been dissected by slope processes and faulting (Fig. 1). In two key locations, one on Chalk Hill Road and one near North Brooks Road, alluvial gravel units dip ~50° within 10 m of the fault (locations shown in Fig. 1)., demonstrating that these units have been deformed and rotated adjacent to individual fault strands. Although not visible in Fig. 1, reconstructing wide channels that hold Windsor Creek, on the west side of the fault, with Pool Creek, east of the fault, also reconstructs two additional channels and reconstructs two bodies of truncated lobate fan structures. These channels have been displaced 5km along the fault. Many smaller offsets also exist along the fault, as in our three slip rate sites. Although most variations in geomorphology and topography along the fault appear to be controlled by local fault geometry or changes in lithology, the landscape has also been significantly modified in some areas by land-use practices. In particular, the development of wineries has led to anthropogenic smoothing of the topography, which complicates assessment of relative geomorphic ages.

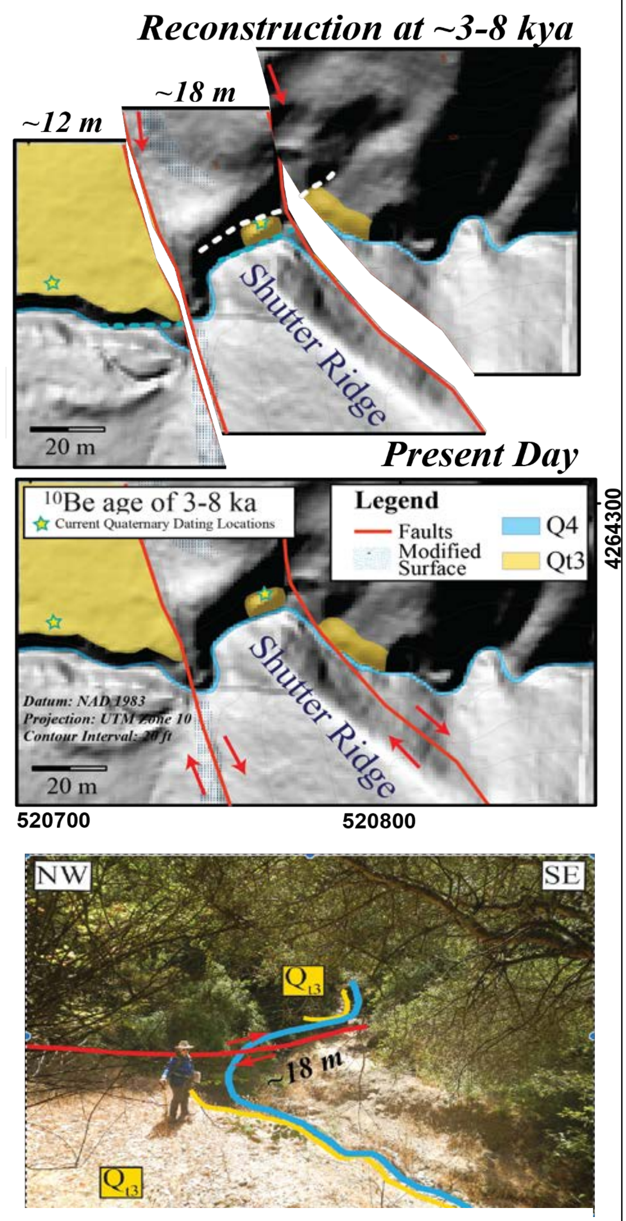

Fig. 2. Slip rate site at Shiloh Regional Park in Sonoma County. Top panel shows reconstructed landscape prior to displacement on the fault at ~3-8 ka. Middle panel shows present day offset of Q_{t3} terrace by one strand of the Rodgers Creek Fault and offset of an incised channel/fan riser offset by another strand. Bottom panel shows a field photo of the ~16- 18 m offset terrace.

Site 1: Offset Channel in Shiloh Ranch Regional Park

In Fig. 2 we summarize findings from our slip rate site in Shiloh Ranch Regional Park in Sonoma County, CA. This site was chosen because of two deflections along a small stream channel created by sub-parallel strands of the Rodgers Creek Fault. The western strand offsets an alluvial fan and an incised channel by ~11-12 m from their source drainage. Removing the offset of ~11-12 m realigns the riser edge of the alluvial fan to the channel wall across the fault. Upstream in the channel that feeds the alluvial fan, the eastern strand offsets this same small channel by an additional ~16-18m. A fluvial terrace, deposited within the channel walls, is also offset ~16-18m along the eastern strand. Removing this offset aligns the edges of the terrace with a geomorphically similar terrace across the fault. Combining these two offsets yield a cumulative displacement of ~27-30 m.

Ten in-situ cosmogenic ^{10}Be samples were collected at this site to constrain the age offsets. Two ^{10}Be exposure surface samples and one ^{10}Be depth profile, containing 5 samples, were collected from the fluvial terrace offset by the eastern fault strand. A single surface clast yielded an exposure age of 9104yr +/- 566yrs. An amalgamated gravel sample yielded an exposure age of 11239 +/- 593yrs. Four depth profile samples were collected from depths between 25 to 130 m. A fifth sample, collected at 190 cm depth from beneath the surface yielded higher concentrations of ^{10}Be than all four overlying samples. We interpret these results to suggest the sample collected at 190 cm is representative of an older deposit and so we did not apply this sample to the ^{10}Be depth profile model age. The remaining four samples produced a ^{10}Be depth profile model age of $4.6\ ^{+3.3}/_{-2.6}$ ka that is corrected for inheritance. This depth profile model age suggests significant inheritance of ^{10}Be concentrations from hillslope residence. Also, the lack of soil development in the terrace suggests a young age. Our present interpretation is that the fluvial terrace and alluvial fan, at the mouth of the stream channel, are of similar age. This interpretation is based on the observation that the terrace and the alluvial fan are of similar elevation, are along the same stream gradient, and appear to be the most recent deposit by the stream, which have since incised into both deposits. A final, three exposure samples have been collected from the surface of the fan to estimate an exposure age for the fan, and confirm or reject this interpretation. Based on current interpretations, we combine the depth profile model age with the cummulaative displacement of ~27-30 m across both strands of the fault to estimate a preliminary rate of 5.4 $^{+4.7}/_{-1.7}$ mm/yr (~4-10 mm/yr) since 4.6 $^{+3.3}/_{-2.6}$ ka. This slip rate may not represent the total slip on the Rodgers Creek fault at this latitude. Additional slip may

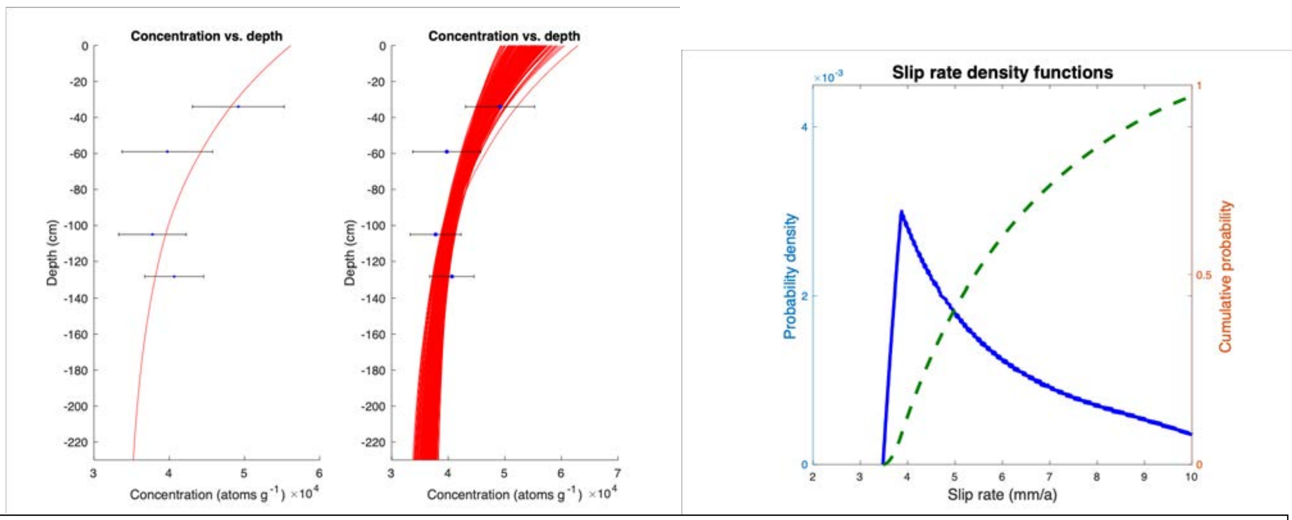

Fig.3. Left: ^{10}Be Concentration (atoms/gram of quartz) versus depth (cm) plots show profile solutions (left) and the X^2 best fit solutions (right) calculated using the depth profile simulator from Hidy et al. (2010). Error bars represent 2σ total measurement error. Right: The probability of possible slip rates (mm/yr) at our slip rate site in Shiloh Ranch Regional Park using depth profile solutions. The blue curve plots slip rate versus probability density. The green dashed curve plots slip rate versus cumulative probability.

be partitioned on to other fault strands mapped east of our slip rate site (Hecker and Randolph Loar, 2018).

<u>Site 2: Offset Channels in Foothill Regional Park</u>

Fig. 4 details a series of offsets within Foothill Regional Park. Here, the Rodgers Creek Fault crosses a number of small and large channels that have been deflected or beheaded

(Fig. 1). These channels show displacement recorded over at least 3 timescales. Fig. 4B shows a reconstruction that removes ~100 m of slip along the fault. In this reconstruction channels 3 and

4 are restored along with two smaller channels, shown by the blue lines (Fig. 4B). The ~230m fault reconstruction (Fig. 4C) removes the deflection from Channel 2 and restores the beheaded Channel 1. This realignment also allows for Channels 3 and 4 to connect with potential source channels across the Rodgers Creek Fault. The ~380m reconstruction (Fig. 4D) connects beheaded Channel 1 with Channel 2 (East) across the Rodgers Creek Fault. Channel 2 (West) connects with Channel 4. An alluvial fan body between Channel 1 and Channel 2 (West) also connects with a fan body that has similar geomorphology between Channel 2 (East) and Channel 4 (Fig 4D). This series of fault reconstructions shows time transgressive motion along the Rogers Creek Fault. Two depth profiles have been collected at this site, one containing 8 samples north of Pond B, and one containing 6 samples south of Pond B. Sample locations are marked by yellow/green stars (Fig. 4A). AMS ratios are needed from 8 of these sample before the depth profiles can be interpreted.

Fig. 4: Fault reconstructions over multiple time intervals in Foothill Regional Park. Blue lines show stream channels that are connected in each reconstruction.

Slip Rate Site 3: ~165m Offset near North Brooks Road

North of Foothill Regional Park, our third slip rate site is located in Chalk Hill Winery, near North Brooks Road (Fig 1, 5). Here, the Rodgers Creek Fault crosses a major, 300m wide paleochannel. Fault mapping suggests that two fault strands transect this wide flat valley leading to the deflection of modern stream channels and terraces within the valley floor (Fig. 5). In the valley bottom, two tributaries of Windsor Creek meet just west of the fault. At the fault, the northern branch (Channel 1 West) is abruptly beheaded. Although a comparatively small channel

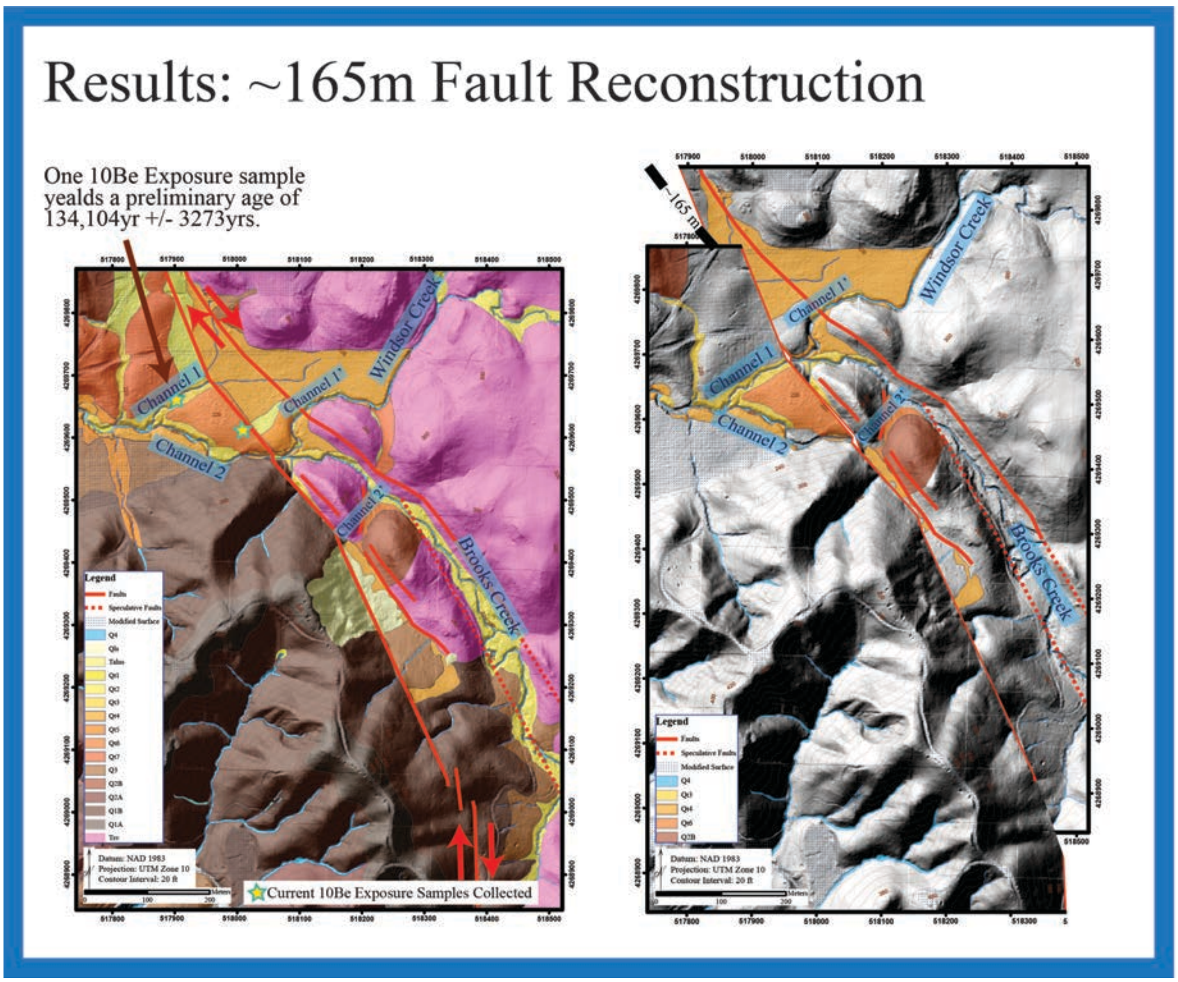

Figure 5: (a; Left) Quaternary geomorphic map of the modern channel configuration. (b; right) The ~165m offset reconstructs the beheaded Channel 1 with Channel 1', the modern channel of Windsor Creek. Channel 2 also realigns with Channel 2', which is an abandoned paleochannel. Yellow stars represent current Quaternary dating locations

continues upstream of the fault, it is much less incised into the floodplain at this point. We hypothesize that this branch (Channel 1 West) was once the main channel southern branch of

Windsor Creek and has been offset ~165 m and beheaded by the fault. Removing 165 m of slipfrom the fault (Fig. 5) also realigns the modern channel of Windsor Creek (Channel 2 West) to a now abandoned drainage between two bedrock knobs (Channel 2' East). This reconstruction also realigns several drainages to the south in Foothill Regional Park. One surface clast exposed in the thalwag of the beheaded and now abandoned channel yielded an exposure age of 134,104+/-3273yr. Additional samples, such as from the opposite side of the fault along the main branch of Windsor Creek, would be needed to constrain the timing of stratigraphic relationships, exposure ages, and inheritances of offset terraces at this site in order to calculate a robust slip rate.

Implications of Preliminary Results:

The goal of our study is to evaluate the temporal and spatial patterns of slip rates along and across the Rodgers Creek Fault. Although we are still working to estimate slip rates over late Pleistocene timescales at Sites 2 and 3 and to narrow the uncertainty of the Holocene rate at Site 1, our initial rate at Site 1 in Shiloh Ranch Regional County Park of 4-10 mm/y may indicate that slip rates are constant along fault strike. This rate is comparable, within their respective uncertainties, to (1) modern slip rates of 7.5+-2.6 mm/yr derived from satellite-based Interferometric Synthetic Aperture Radar (InSAR) studies [*Funning et al., 2007; Jin & Funning, 2017*], (2) geodetic slip rates of 6.6+-2.4mm/yr [*d'Alessio et al., 2005*], and (3) paleoseismic studies along the southern trace of the Rodgers Creek Fault of 6.4-10.4 mm/yr [*Schwartz et al., 1992; Budding et al., 1991*]. These rates also overlap with long-term geologic slip rates of 5-8 mm/yr for the Rodgers Creek Fault, since the fault transitioned to dextral strike slip motion around 3 Ma [*McLaughin et al., 2012*]. Constant fault slip rates on the Rodgers Creek Fault also implies that the fault is relatively mature, strain-weakened, and straight. This rate for the northern segment of the Rodgers Creek Fault is also comparable with geologic slip rates of 7-9 mm/yr for the Hayward fault [*Lienkaemper & Borchardt. 1996*].

References:

Baldwin, J., Koehler, R., and Thompson, S., 2004, Preliminary Late Pleistocene Slip Rate of the Green Valley Fault at Lopes Ranch Creek, Cordelia, California, *in* AGU Fall Meeting Abstracts.

Blake, M., Graymer, R.W., and Stamski, R., 2002, Geologic map and map database of western Sonoma, northernmost Marin, and southernmost Mendocino counties, California, US Geological Survey.

Budding, K.E., Schwartz, D.P., and Oppenheimer, D.H., 1991, Slip rate, earthquake recurrence, and seismogenic potential of the Rodgers Creek Fault zone, northern California: Initial results: Geophysical Research Letters, v. 18, p. 447–450, doi: 10.1029/91GL00465.

d'Alessio, M.A., 2005. Slicing up the San Francisco Bay Area: Block kinematics and fault slip rates from GPS-derived surface velocities. J. Geophys. Res. 110, B06403.

Delattre, M., 2011: Preliminary geologic map of the Healdsburg 7.5 ′ quadrangle, Sonoma County, California: A digital database: California Geological Survey, Sacramento, California.scale: 1: 24,000.

Evans, E. L., Loveless, J. P., & Meade, B. J. (2012). Geodetic constraints on San Francisco Bay Area fault slip rates and potential seismogenic asperities on the partially creeping Hayward fault. Journal of Geophysical Research, 117(B3), 17,315–15. http://doi.org/10.1029/2011JB00839

Field, E. H., T. E. Dawson, K. R. Felzer, A. D. Frankel, V. Gupta, T. H. Jordan, T. Parsons, M. D. Petersen, R. S. Stein, R. J. Weldon II, and C. J. Wills (2009) Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 3), Bulletin of the Seismological Society of America, Vol. 99, No. 4, p 2053-2107.

Funning, G.J., Burgmann, R., Feretti, A., Novali, F., and Fumagalli, A., 2007, Creep on the Rodgers Creek Fault, northern San Francisco Bay area from a 10 year PS-InSAR dataset: Geophysical Research Letters, v. 34, L19306, doi: 10.1029/2007GL030836

Grove, K., Niemi, T.M., 2005. Late Quaternary deformation and slip rates in the northern San Andreas fault zone at Olema Valley, Marin County, California. Tectonophysics 401, 231–250.

Hecker, S., Langenheim, V.E., Williams, R.A., Hitchcock, C.S., and DeLong, S.B., 2016, Detailed mapping and rupture implications of the 1 km releasing bend in the Rodgers Creek fault at Santa Rosa, northern California: Bulletin of the Seismological Society of America, v. 106, no. 2, p. 575–594, https://doi.org/10.1785/0120150152.

Hecker, S., and Randolph Loar, C., 2018, Map of Recently Active Traces of the Rodgers Creek Fault, Sonoma County, California: US Geological Survey Scientific Investigations Map, v. 3410.

Kelson, K.I., Baldwin, J.N., and Randolph, C.E., 19 98, Late Holocene slip rate and amounts of coseismic rupture along the central Calaveras fault, San Francisco Bay area, California: Final Technical Report submitted to the U.S. Geological Survey NEHRP, Award 1434-HQ-97-GR-03151, 26 p.

Langenheim, V.E., McLaughlin, R.J., McPhee, D.K., Roberts, C.W., and McCabe, C.A., 2008, Geophysical framework of the Santa Rosa 7.5′ quadrangle, California, in McLaughlin, R.J., et al., eds., Geologic and geophysical framework of the Santa Rosa 7.5′ quadrangle, Sonoma County, California: U.S. Geological Survey Open-File Report 2008–1009, p. 34–45, http://pubs.usgs.gov/of/2008/1009/.

Langenheim, V.E., Graymer, R.W., Jachens, R.C., McLaughlin, R.J., Wagner, D.L., and Sweetkind, D.S., 2010, Geophysical framework of the northern San Francisco Bay region, California: Geosphere, v. 6, p. 594–620, doi: 10.1130/GES00510.1.

Lienkaemper, J. J., and G. Borchardt (1996), Holocene slip rate of the Hayward fault at Union City, California, J. Geophys. Res., 101(B3), 6099–6108, doi:10.1029/95JB01378.

McLaughlin, R.J., and Nilsen, T.H., 1982, Neogene non-marine sedimentation and tectonics in small pull-apart basins of the San Andreas fault system, Sonoma County, California: Sedimentology, v. 29, no. 6, p. 865-876.

McLaughlin, R., Sarna-Wojcicki, A., Fleck, R., Wright, W., Levin, V., and Valin, Z., 2004, Geology, tephrochronology, radiometric ages, and cross sections of the Mark West Springs 7.5′ quadrangle, Sonoma and Napa Counties, California: US Geological Survey Scientific Investigations Map, v. 2858.

McLaughlin, R.J., Sarna-Wojcicki, A.M., Wagner, D.L., et al., 2012, Evolution of the Rodgers Creek-Maacama right-lateral fault system and associated basins east of the northward-migrating Mendocino triple junction, Northern California: Geosphere (Boulder, CO), v. 8, no. 2, p. 342-373, 32.

McPhee,D.K.,V.E.Langenheim,S.Hartzell,R.J.McLaughlin,B.T.Aagaard,R. C. Jachens, and C. McCabe (2007). Basin structure beneath the SantaRosa plain, northern California: Implications for damage caused bythe 1969 Santa Rosa and 1906 San Francisco earthquakes,Bull. Seis-mol. Soc. Am.97,no.5,1449–1457, doi:10.1785/0120060269.

Prentice, C.S., Larsen, M.C., Kelsey, H.M., and Zachariasen, J., 2014, Late Holocene slip rate and ages of prehistoric earthquakes along the Maacama Fault near Willits, Mendocino County, northern California: Bulletin of the Seismological Society of America, v. 104, no. 6, p. 2966-2984.

Schwartz, D.P.P., D; Hecker, Suzanne; Okumura, Koji; Budding, Karin E; Powers, T J, 1992, The Rodgers Creek Fault zone; fault behavior and earthquake potential: Calif. Div. Mines Geol., Spec. Pub., v. 113, p. 63.

Wagner, D.L., and Gutierrez, .I., 2017, Geologic map of the Napa 30′ x 60′ Quadrangle, California: California Geological Survey.

Watt, J., Ponce, D., Parsons, T., & Hart, P. (2016). Missing link between the Hayward and Rodgers Creek Faults. *Science Advances.*

(4) **Bibliography: None**

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